1.0 INTRODUCTION:

Welding is the most widely used, cost-effective and versatile mode of joining technique that produces a joint compatible to the strength of the adjoining base plates. The process can be made suitable to meet any stringent requirements from welding, whether it is nuclear power plants, spacecraft, deep-diving submarines, high-pressure pipelines, elevated and cryogenic temperature usage or even underwater applications. By definition it states, “a process of joining of materials by application of heat or pressure or both, with or without addition of filler metal to produce a localized union either by recrystallization or by fusion at the interface.”

The history of welding starts from around 2000 years ago when people began to pressure weld the noble metals. The process of forge welding started about 1500 years back when man learnt the art of manufacturing wrought iron, heating the iron pieces to dull red and then hammering them together. The Iron pillar of Delhi, construction of Konark temple in Orrisa, well-known Sword of Damascus are the few to name for carrying the memorandum of the traditional welding skills of our ancestors.

The modern implementation of welds is only little more than 100 years old. In the early 1880s, the acetylene torch and electric arc were introduced as tools capable of fusion welding though it was not highly acceptable to the fabricators compared to riveting and bolting. The welding received a special impetus only during World-war II, due to the need of a faster fabrication technique of making and maintenance of ships, tanks, trucks, air-crafts etc. A significant improvement has taken place in the last fifty years in terms of its process, science and technology. Not alone the metallic materials, people have successfully welded ceramic materials too. The technology is available to weld materials as thick as few feet to few mils maintaining the desired level of quality.

A large volume of literature and books are now available to assist in proper planning, designing, reasoning and characterizing the weld metal before, during and after welding. Each year approximately 5000 specialized articles, papers, documents, books are published, and add to the world’s data-bank on welding. This tremendous mass of welding information has fortunately been digested in electronic format and organized in data-bases and programs to permit rapid searching and selection of materials.

Welding encompasses knowledge of both Process & Physical Metallurgy comprehending to a specialized view-point. As for example, arc welding can be compared to the conventional molding and casting. The electrode stick is the hand held electric furnace, from which the liquid metal is continuously poured into the suitably designed metal mold. In conventional casting the mold-metal reaction is undesirable whereas it is extremely essential for arc welding to obtain a sound weld joint. So, it involves the knowledge of process metallurgy too. The structure of metals changes when they are put through or suffer from elevated temperature. This change is intrinsic and characteristic to each and every metal/ alloy. Thus the base plates (acting as the metal mold), undergo metallurgical changes depending on welding conditions, heat input, thermal conductivity and composition of the material. Most often these are detrimental to the quality of the welded assembly. To avoid such undesirable effects, selective procedures are followed for individual material with judicious judgment for preheat (to cut down the heat flow rate) or post-weld treatment (to recover the metallurgical damage) of the welded structure.

2.0 WELDABILITY:

By definition, it is the capacity of a metal or combination of metals to be welded under fabricating conditions into a specific and suitably designed structure to meet satisfactorily the demands in the intended service. So, from the definition itself it is very clear that there are two aspects of weldability- one related to how a material can be welded which is known as fabrication weldability while the other is related to the behaviour of an weldment in service i.e., service weldability. The factors governing the fabrication weldability and service weldability are as follows:

Fabrication Weldability	Service Weldability
1. Joint design. 2. Chemical composition of parent metal. 3. Surface condition of the parent metal. 4. Welding techniques and sequences. 5. Heat input. 6. Soundness required from the weld metal.	1. Environment to which the weldment is to be exposed. 2. Alloying elements in parent steel. 3. Effect of steel processing. 4. Filler metal composition. 5. Weld metal microstructure. 6. Pre/ post weld heat treatment. 7. Weld metal mechanical properties.

The mandatory requirements from a welded joint always depend on its end use. These essentially vary according to the material and criticality of applications. Majority of the welding fabrication codes therefore specify the following for the welded joint:

1. The chemical composition,
2. The minimum mechanical properties- UTS, YS, elongation, impact, bend etc.

3.0 WELD METAL MICROSTRUCTURE:

The solidification microstructure is dependent on weld pool solidification conditions i.e. the material characteristics and welding parameters. As the travel speed increases, the shape of the weld pool changes from roughly oval to elliptical to tear drop shaped (fig. 1a & 1b). Assuming two-dimensional heat flow, the solidification rate (R) at different regions along the weld pool can be estimated as R = V Cosθ where V is the travel speed and θ is the angle between the centre line of the weld and at any point 'D' on the solid-liquid interface (as shown in figure).

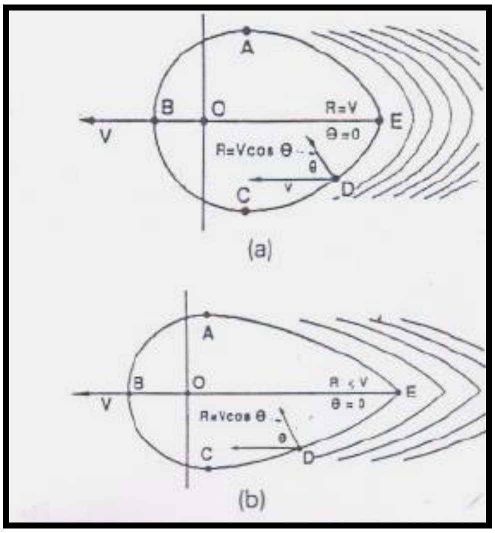

Figure-1: Variation in weld pool shape as a function of travel speed.

Formation of a planar, cellular or dendritic sub-structure during solidification is largely determined by R and G (the temperature gradient along the weld pool). If a weld is deposited at constant travel speed, by inducing steep temperature gradient (G1), as shown in fig. 2, a planar grain structure is formed without any constitutional supercooling. But as the temperature gradient decreases, the liquid ahead of the interface becomes rich in solute than the cell core and suffer more and more degree of supercooling. Therefore a cellular or dendritic substructure appears with G2, G3 gradient (as shown in fig.2d).

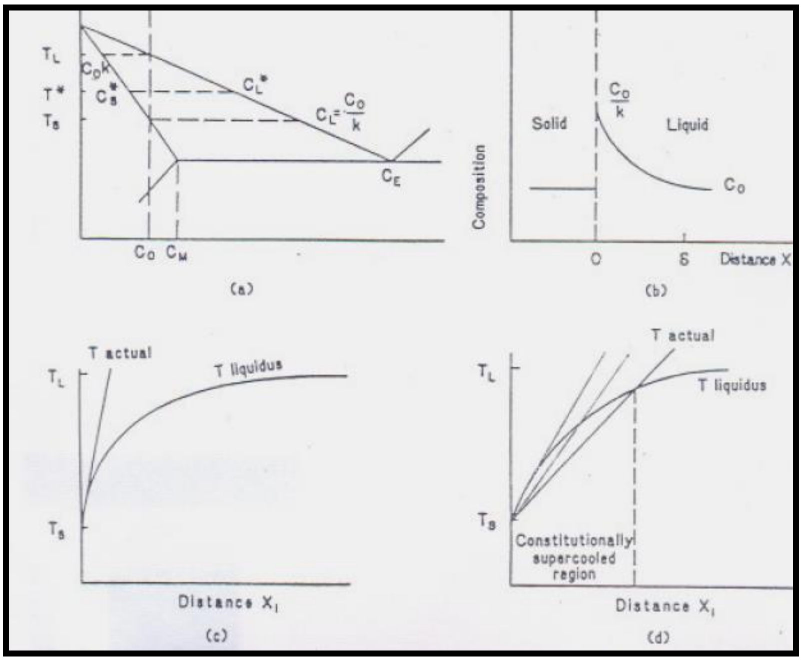

Figure-2: Schematic diagram showing a) a simple phase diagram of cpmposition Co, b) plot of the variation in the solute concentration as a function of distance from the solid-liquid interface, c) planner solidification (no constitutional supercooling), d) cellular or dendritic solidification (constitutional supercooling).

The formation of these structures with solidification parameters is schematically shown in fig. 3. A slower growth rate promotes equiaxed dendritic structure.

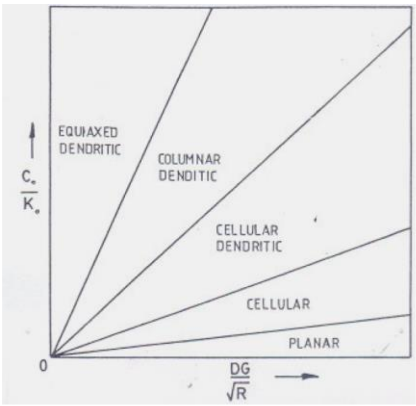

Figure-3: Schematic representation of solidification patterns as a function of thermal & constitutional variables.

<u>4.0 HEAT AFFECTED ZONE (HAZ)</u>:

The base metal suffers a complex thermal cycle wherein all temperatures from melting down to warming are involved in the vicinity of the weld. The effect of these temperatures is not realized below lower transition temperature (A_{C1}) but substantial metallurgical changes take place when the plates suffer a temperature beyond A_C till the solid-liquid transition zone. These various changes in the HAZ are schematically shown in fig. 4. Structural changes have been compared with the Fe-Fe_3C diagram. A coarsening or refining of the parent metal microstructure appears in association with the changes of phase like, martensite or coarse/ fine pearlite etc. These metallurgical changes determine the strength, hardness, ductility, resistance to impact, resistance to corrosion and similar mechanical & physical properties. Therefore, it is very important to know such changes to ascertain the final condition of the structure after welding. The hardest part of the hardened zone lies just below the fusion line. The first reason is that the metal passes more quickly through the temperature (about 700°C) where the softer constituent pearlite starts to form and secondly the coarse grain structure tends to harden more readily than does a fine grained structure.

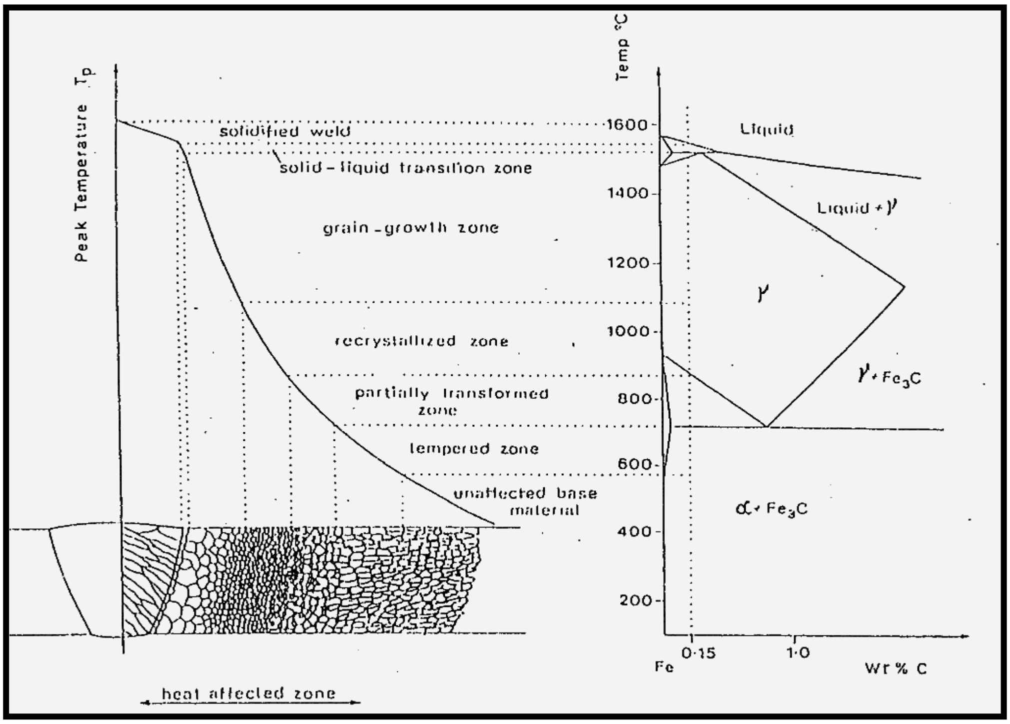

Figure-4: Schematic representation of HAZ microstructures of a 0.15%C-steel along with corresponding temperature positions in the Fe-Fe_3C equilibrium diagram.

<u>5.0 EFFECT OF ALLOYING ELEMENTS IN THE C-Mn STEEL WELD METAL:</u>

5.1 Effect of Carbon

- Linearly increases the yield and tensile strength.
- The hardness increases.
- Promotes precipitation of the secondary phases.
- The optimum C at 1.4% Mn for improved mechanical properties is 0.06 to 0.09.

5.2 Effect of Manganese

- Increased from 0.6 to 1.8%, acicular ferrite percentage increases.
- Increasing Mn, refines the acicular ferrite of the as-deposited weld metal, that improves the notch toughness of the weld metal
- YS and UTS of the weld deposits increase almost at a rate 10 MPa / 0.1%.

5.3 Effect of Silicon

- Increasing Si, weld metal oxygen content decreases.
- Hardness, YS and UTS increases with Si.
- Notch toughness is deteriorated with same Mn content.
- A maximum 0.5% Si content is tolerated at an optimum Mn in as-weld applications.

5.4 Effect of Chromium

- Acicular ferrite increases with Cr but beyond ~ 1.0%, it decreases again. The M/A fraction increases and ultimately at 2.3% Cr, the structure is entirely covered with ferrite colonies containing partially aligned or unaligned second phases.
- On PWHT, dissociation of microphases takes place to form precipitates at cell or grain boundaries. The toughness is thus reduced significantly. The extent of deterioration depends on Mn content and optimum Mn for same is 1.0%.
- Addition of Cr markedly affects the etching response of the weld metal. The visual response of a build up weld metal, as obtained from macro-sections becomes blurred with increasing Cr.
- Hardness, YS and UTS increases with increase in Cr.
- In as-welded condition toughness is adversely affected beyond 1.0%.

5.5 Effect of Nickel

- The proportion of primary ferrite reduces in as-deposited weld metal and acicular ferrite increases with Ni content. Proportion of polygonal ferrite also reduces except at high Mn level when martensitic transformation is favored.
- Like Cr addition, the presence of Ni affect the etching characteristics. Microstructural banding and chemical heterogeneity increases with Ni due to micro-segregation.
- Hardness of weldments, YS and UTS increases with Ni addition.
- Ni is beneficial for cleavage resistance at low Mn and deleterious at high Mn contents. Pick toughness displaces from 1.4% Mn to 0.6% Mn.
- SR may induce severe embrittlement when Ni and Mn are not properly balanced. Notch toughness decreases after SR and addition of Ni in high Mn (>1.5%) weld metal promotes carbide precipitation. Commercial 1%Ni (E 7018-G), 2.25% Ni (E 7018-C1) and 3.25% Ni (E7018-C2) electrodes are set to yield 1.2%, 0.8% and 0.6% Mn in the deposit. But higher Mn base plate may cause toughness degradation.
- In general, overall benefit of Ni addition in the as-weld mechanical properties and after SR is not so significant.

5.6 Effect of Molybdenum

- Primary ferrite is progressively reduced in as deposited weld metal.
- The proportion of acicular ferrite is increased up to 0.5% Mo, then subsequently decreases.
- Hardness, YS and UTS of the deposited weld metal increases with Mo. It has a greater influence on the strength of the deposit than Mn. Following SR, the decrease in impact strength with increase in Mn at a constant Mo is less compared to increase of Mo at a constant Mn value, Mo causes a reversal in the impact properties above 0.25%.
- The charpy impact value falls after SR, especially above 0.5% Mo.
- Optimum Mo is kept ~ 0.25% at 1.0% Mn.

5.7 Effect of Niobium

- The microstructure of as-deposited metal gets modified with increased formation of ferrite with second phase.

- The hardness, YS and UTS increases with increase in Nb.
- Notch toughness of both as-welded and stress-relieved weld metal, was drastically impaired at all levels of Mn.
- Nb should be kept as low as possible.

5.8 Effect of Vanadium

- Increases the acicular ferrite in as-deposited weld metal.
- The hardness, YS and UTS increases with increase in V.
- In the as-welded condition the notch toughness gets marginally improved with V and at a Mn level of ~ 0.65%, but after SR the toughness decreases at all levels of Mn.
- In general, maximum 200 ppm V can be tolerated without degradation after PWHT.

5.9 Effect of Titanium

- The weld metal O_2 content decreases with Ti.
- Acicular ferrite (AF) percentage increases with Ti in weld metal. Volume % of AF increases upto 30 ppm and thereafter decreases. At ~ 100 ppm Ti a further progressive increase of AF takes place.
- The hardness of weld metal increases.
- Tensile values also increase with increase of Ti.
- Two optima in impact properties are reported, one at 30 ppm and another at 200 ppm Ti.

5.10 Effect of Boron

- The addition of B increases the acicular ferrite and decreases primary ferrite in weld metal microstructure. However, the the effect reduces drastically without sufficient addition of Ti and vice versa.
- The role of Ti is mainly to protect B from nitrogen and oxygen by forming titanium nitride (TiN) in the liquid state prior to solidification. The optimum Ti content again is a function of nitrogen and nitride formers.
- The BN acts as a nucleating agent for acicular ferrite formation.

- Only controlled addition increases the volume percentage of acicular ferrite. Beyond the optimum value (depend also on other alloying elements and welding procedure), it promotes upper bainite structure which exerts detrimental influences on weld metal toughness.
- A large volume fraction (upto 95%) of acicular ferrite can be obtained by maintaining B and Ti contents between 40-45 ppm and between 400-500 ppm respectively.

5.11 Effect of Copper

- A general refinement of microstructure is reported with increasing Cu in the weld.
- In the as-welded state, volume fraction of second phase increases due to austenite stabilizing characteristics of Cu.
- Addition of Cu does not affect the chemistry and distribution of non-metallic inclusions.
- Even 1.4% Cu promote segregation, therefore addition is restricted.
- Stress relief treatment leads to 1) precipitation & spherodisation of carbides and 2) ε-Cu precipitation in the grain boundary even for 0.66% and 1.4% Cu welds.
- Excellent impact toughness properties are preserved up to 0.66% Cu for both as-welded and stress relieved state.
- Addition of Cu increases hardness, strength and resistance to corrosion.

5.12 Effect of Aluminium

- Weld metal O_2 content remains constant with increase of Al.
- Total and residual N_2 content of the weld decreases but free N_2 remains invariable.
- Weld metal acicular ferrite initially decreases then increases and reaches maximum at 150-200 ppm Al.
- The mean composition of the non-metallic inclusions changes, Al_2O_3 replaces MnO and SiO_2. The inclusion diameter usually remains unchanged (between 0.32 to 0.38 micron)
- YS and UTS increases but after SR both are decreased.
- Optimum notch toughness is achieved at zero and 350 ppm of Al.

5.13 Effect of Sulfur & Phosphorous

- S & P both are in general detrimental to the weld metal, increases the volume % of inclusions.
- S increases the volume fraction of ferrite with aligned M-A-C in the as-deposited weld metal; the change is attributed to the existence of a layer of MnS on the surface of the inclusions.
- S lowers hardness, decreases tensile strength and drastically reduces notch toughness.
- P increases hardness and tensile properties but had little effect on notch toughness (studied in the range 0.007 to 0.040%).
- Little benefit is gained by reducing S and P much below 0.005%.

5.14 Effect of Oxygen

- Along with other compositional variables, O_2 strongly influences structural steel weld metal microstructure and mechanical properties.
- High weld metal O_2 content promotes the formation of primary ferrite, whereas controlled amount of O_2 maximises acicular ferrite in the microstructure.
- O_2 shifts the C-C-T curves towards left i.e, moves the C-curves to shorter times.
- Weld metal toughness is a function of O_2 and Mn cncentration. At low O_2 contents, less than 100 ppm, provide less number of nucleation sites and favour ferrite with second phase. On the otherhand, at high O_2 contents, grain boundary ferrites predominate. But over 800 ppm O_2 content is detrimental because of the increase in the population densities and size of the inclusions in the weld metal.
- An optimum of 400 ppm of O_2 is desirable to achieve the desired toughness level.

5.15 Effect of Iron powder

- A minor deterioration in toughness takes place with increase in Fe powder in the coating.
- Commercial plain C-Mn E7018 type electrodes have superior impact properties to E7016 type consumables.
- Iron powder upto 30% can be added through coating with suitable flux design.

5.16 Effect of heat Input

- The weld metal Mn and Si content decreases with heat input (HI).
- The hardness of the as-deposited weld metal decreases with increase in HI.
- The average width of the columnar grain increases at higher HI.
- The amount of pro-eutectoid ferrite increases at the expense of acicular ferrite. A coarse microstructure is formed.
- The YS and UTS decreases on high HI>
- Optimum impact properties are obtained with ~ 1.5 kJ/mm heat input.

5.17 Effect of Stress Relief heat treatment

- The morphology of second phase particles changes by breaking down to ferrite and carbide.
- Pearlite and cementite films are spherodised.
- Develops grain boundary carbides and subsequently coarsens with time.
- The hardness of deposited and reheated regions decreases.
- The YS and UTS decreases.
- Notch toughness improves at low C (0.45%) and Mn (~ 1.4% is the peak) level but deteriorates at high C and Mn level.
- The optimum toughness is achieved with 0.07-0.09% C and 1.4% Mn .

5.18. Effect of heat treatment

The effect of normalising in the range of 800-1000°C and tempering in multirun weld deposits are studied.

- The ferrite grain size increases with increasing temperature.
- The ferrite grain size decreases with increasing Mn content but total amount of second phase increases.
- The hardness, YS and UTS decreases.

- The notch toughness deteriorates but the optimum is at 1.5% Mn level.

5.19 Effect of Inter-pass temperature

- Studied for 1.0 kJ/ mm HI, increasing interpass temperature from 20° to 300°C reduces the Mn and Si level in the weld deposits.
- Increased interpass temperature coarsens the microstructure of the as-deposited weld metal and reduces the volume fraction of acicular ferrite.
- It lowers the YS & UTS, the loss depends on the weld metal Mn content.
- The optimum Mn content with regard to impact properties at any given interpass temperature is 1.4%.

5.20 Effect of Electrode diameter

- Weld metal Mn and Si content reduces with increasing electrode diameter.
- Number of layers decreases and the nugget and recrystallised areas increase with higher diameter electrode.
- The relative percentage of the microstructural constituents of the as-deposited weld metal remains unchanged, but the lath size of the acicular ferrite increases. The average width of the columnar grains increases.
- The microstructure of the high temperature reheated region is coarsened, the width of ferrite envelopes increases. The size of the equiaxed grains also increases.
- Hardness along the X-section of the deposit varies correspond to the refined zones.
- The YS and UTS decreases but not to a marked extent.
- Notch toughness is deteriorated with higher electrode diameter.

5.21 Effect of Welding position

The following points are noted on reverting the welding position from flat to the vertical up position at an equivalent heat input.

- The weld metal C, Mn, Si and O_2 increase and N_2 content decreases.
- No significant changes take place in the refined zones and in hardness .

- The YS and UTS remain unaffected.
- Impact at 1.4% Mn is considered to be optimum. The impact temperature goes down with limited weaving rather than full weaving at the time of vertical up welding.

6.0 HYDROGEN-INDUCED CRACKING (HIC) IN WELDMENTS:

Hydrogen-induced cracking is also known as cold cracking or delayed cracking or under-bead cracking. It also occurs in steel during manufacture, during fabrication and in service. It is thus not confined to welding, but when it occurs as a result of welding the cracks are either in the heat affected zone (HAZ) of the parent metal or in the weld metal itself.

6.1 Cracking in the HAZ

The conditions favourable for cracking can be summarized as –

1. **Presence of Hydrogen**- derived from moisture in the fluxes used in welding and from other sources.
2. **Tensile stresses act on the weld**- these stresses form due to thermal fluctuations during welding and rigidity of the joint.
3. **A susceptible HAZ micro-structure**- coarse grained region, martensitic microstructure formed during welding.

6.2 Cracking in the Weld metal

As the alloying content of both weld metal & parent metal increases, the susceptibility of cracking in the weld increases. If they originate in the root they are longitudinal to the weld. If they are buried or are at the surface, they may be trans-granular to the weld.

During welding, hydrogen is absorbed by the weld pool from the arc atmosphere. Though, much of this hydrogen escapes during cooling from the solidified bead by diffusion but some also diffuses out into the HAZ and the parent metal. This distribution depends on several factors, such as the original amount absorbed, the size of the weld, the decreasing solubility and the time-temperature conditions of cooling.

In general, more hydrogen present increases the risk of cracking. The principal sources of hydrogen from the material to be welded are:

1. Oil, grease, dirt, rust, paint, etc on the surface and adjacent to the weld preparation.

2. Degreasing fluid used to clean surfaces before welding.

The principal sources of hydrogen in the welding consumables are:

1. Moisture in the coating of MMAW electrodes, fluxes in the SAW process and the fluxes used for FCAW process.

2. Any other hydrogenous compounds in the coating flux.

3. Oil, dirt, grease, etc either on the surface or trapped in the surface layers of welding wires and electrode core wires.

4. Presence of rust on the surface of the base metal or on the welding wires.

6.3 Measures to avoid Hydrogen Induced Cracking (HIC)

The steps to reduce the propensity for HIC can be summarized as:

1. Re-dry the SMAW electrode and SAW flux at 300-350°C for 2 hours or as per the recommendations of the consumable manufacturer prior to use.

2. Preheat & inter-pass temperature depending on the chemistry & joint thickness.

3. Proper joint fit up to reduce the restraints.

4. Cleanliness of the adjoining surfaces

5. Multi-run welding procedure.

6. Post weld heat treatment.